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Lukin, Mikhail D.

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Harvard University
Physics Department
17 Oxford Street
Cambridge, MA 02138

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14. ABSTRACT

Key progress includes demonstration of a fiber-optical switch that is activated at tiny energies corresponding to few hundred optical photons per pulse. This is achieved by simultaneously confining both photons and a small laser-cooled ensemble of atoms inside the microscopic hollow core of a single-mode photonic crystal fiber and using quantum optical techniques for generating slow light propagation and large nonlinear interaction between light beams. In addition, we demonstrated a strong coupling between NV centers and photonic crystal nanocavity suitable for experiments on single photon nonlinear optics. Finally we developed a new all-electrical surface plasmon (SPP) detection technique based on the near-field coupling between guided plasmons and a nanowire field-effect transistor and realized a new quantum optical medium based on buffer-gas cooled Rb vapor cell.

15. SUBJECT TERMS

slow light, optical photons, photonic crystal nanocavity, plasmon, buffer-gas cooled Rb vapor cell

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Professor Mikhail D. Lukin

Harvard University
Physics Department
17 Oxford Street
Cambridge, MA 02138

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Slow Light:
Novel Techniques for Optical Signal Processing Based on Stationary Pulses of Light

Mikhail Lukin
Agreement number: FA9550-04-1-0455

Status of Effort

Key progress includes demonstration of a fiber-optical switch that is activated at tiny energies corresponding to few hundred optical photons per pulse. This is achieved by simultaneously confining both photons and a small laser-cooled ensemble of atoms inside the microscopic hollow core of a single-mode photonic crystal fiber and using quantum optical techniques for generating slow light propagation and large nonlinear interaction between light beams. In addition, we demonstrated a strong coupling between NV centers and photonic crystal nanocavity suitable for experiments on single photon nonlinear optics. Finally we developed a new all-electrical surface plasmon (SPP) detection technique based on the near-field coupling between guided plasmons and a nanowire field-effect transistor and realized a new quantum optical medium based on buffer-gas cooled Rb vapor cell.

Accomplishments

We described and experimentally demonstrated a technique for deterministic, large coupling between a photonic crystal (PC) nanocavity and single photon emitters. The technique is based on in situ scanning of a PC cavity over a sample and allows the precise positioning of the cavity over a desired emitter with nanoscale resolution. The power of the technique is demonstrated by coupling the PC nanocavity to a single nitrogen vacancy (NV) center in diamond, an emitter system that provides optically accessible electron and nuclear spin qubits.

We showed that superradiant optical emission can be observed from the polarized nuclear spin ensemble surrounding a single photon emitter such as a single quantum dot (QD) or Nitrogen-Vacancy (NV) center. The superradiant light is emitted under optical pumping conditions and would be observable with realistic experimental parameters.

We proposed a new protocol for implementing the two-qubit photonic phase gate. In our approach, the π phase is acquired by mapping two single photons into atomic excitations with fermionic character and exchanging their positions. The fermionic excitations are realized as spin waves in a spin chain, while photon storage techniques provide the interface between the photons and the spin waves. Possible imperfections and experimental systems suitable for implementing the gate are discussed.

Techniques for imaging and manipulating individual quantum emitters with high spatial resolution are essential in areas ranging from single molecule spectroscopy to interfacing emitters in quantum networks. Optical cavities enable strong light-matter interaction and, when coupled to suitable imaging platforms, enable new approaches for single-atom microscopy. We demonstrated a scanning cavity nanoscope (SCN), based on a photonic crystal cavity, that enables simultaneous nanoscale localization of solid-state quantum emitters and modification of emitter properties via the Purcell Effect. We illustrated the power of the SCN by coupling individual nitrogen vacancy (NV) centres in diamond to the nanocavity. Scanning over an NV results in strong position-dependent modification of the spontaneous emission (SE) spectrum, including a six-fold enhancement of the SE intensity at the cavity frequency. The scanning nanocavity overcomes the traditional trade-off between spatial resolution and collection efficiency of near-field optical probes and enables a deterministic photonic interface for a wide range of quantum emitters.

We presented a theoretical technique for solving the quantum transport problem of a few photons through a one-dimensional, strongly nonlinear waveguide. We specifically considered the situation where the evolution of the optical field is governed by the quantum nonlinear Schrodinger equation (NLSE). Although this kind of nonlinearity is quite general, we focus on a realistic implementation involving cold atoms loaded in a hollow-core optical fiber, where the atomic system provides a tunable nonlinearity that can be large even at a single-photon level. In particular, we show that when the interaction between photons is effectively repulsive, the transmission of multi-photon

components of the field is suppressed. This leads to anti-bunching of the transmitted light and indicates that the system acts as a single-photon switch. On the other hand, in the case of attractive interaction, the system can exhibit either anti-bunching or bunching, which is in stark contrast to semiclassical calculations. We showed that the bunching behavior is related to the resonant excitation of bound states of photons inside the system.

We theoretically studied the transmission of few-photon quantum fields through a strongly nonlinear optical medium. We developed a general approach to investigate non-equilibrium quantum transport of bosonic fields through a finite-size nonlinear medium and apply it to a recently demonstrated experimental system where cold atoms are loaded in a hollow-core optical fiber. We showed that when the interaction between photons is effectively repulsive, the system acts as a single-photon switch. In the case of attractive interaction, the system can exhibit either anti-bunching or bunching, associated with the resonant excitation of bound states of photons by the input field. These effects can be observed by probing statistics of photons transmitted through the nonlinear fiber.

Quantum repeaters based on atomic ensemble quantum memories are promising candidates for achieving scalable distribution of entanglement over long distances. Recently, important experimental progress has been made toward their implementation. However, the entanglement rates and scalability of current approaches are limited by relatively low retrieval and single-photon detector efficiencies. We proposed a scheme which makes use of fluorescent detection of stored excitations to significantly increase the efficiency of connection and hence the rate. Practical performance and possible experimental realizations of the new protocol are discussed.

We described a method for controlling many-body states in extended ensembles of Rydberg atoms, forming crystalline structures during laser excitation of a frozen atomic gas. Specifically, we predict the existence of an excitation number staircase in laser excitation of atomic ensembles into Rydberg states. Each step corresponds to a crystalline state with a well-defined of regularly spaced Rydberg atoms. We showed that such states can be selectively excited by chirped laser pulses. Finally, we demonstrated that, sing quantum state transfer from atoms to light, such crystals can be used to create crystalline photonic states and can be probed via photon correlation measurements.

We proposed and analyzed a scheme to interface individual neutral atoms with nanoscale solid-state systems. The interface is enabled by optically trapping the atom via the strong near-field generated by a sharp metallic nanotip. We showed that under realistic conditions, a neutral atom can be trapped with position uncertainties of just a few nanometers, and within tens of nanometers of other surfaces. Simultaneously, the guided surface plasmon modes of the nanotip allow the atom to be optically manipulated, or for fluorescence photons to be collected, with very high efficiency. Finally, we analyzed the surface forces, heating and decoherence rates acting on the trapped atom.

Photonic circuits can be much faster than their electronic counterparts, but they are difficult to miniaturize below the optical wavelength scale. Nanoscale photonic circuits

based on surface plasmon polaritons (SPPs) are a promising solution to this problem because they can localize light below the diffraction limit. However, there is a general trade-off between the localization of an SPP and the efficiency with which it can be detected with conventional far-field optics. Here, we described a new all-electrical SPP detection technique based on the near-field coupling between guided plasmons and a nanowire field-effect transistor. We used the technique to electrically detect the plasmon emission from an individual colloidal quantum dot coupled to an SPP waveguide. Our detectors are both nanoscale and highly efficient (~0.1 electrons per plasmon), and a plasmonic gating effect can be used to amplify the signal even higher (up to 50 electrons per plasmon). These results may enable new on-chip optical sensing applications and are a key step towards 'dark' optoplasmonic nanocircuits in which SPPs can be generated, manipulated and detected without involving far-field radiation.

We demonstrated a fiber-optical switch that is activated at tiny energies corresponding to a few hundred optical photons per pulse. This is achieved by simultaneously confining both photons and a small laser-cooled ensemble of atoms inside the microscopic hollow core of a single-mode photonic-crystal fiber and using quantum optical techniques for generating slow light propagation and large nonlinear interaction between light beams.

We demonstrated that buffer-gas cooling combined with laser ablation can be used to create coherent optical media with high optical depth and low Doppler broadening that offers metastable states with low collisional and motional decoherence. Demonstration of this generic technique opens pathways to coherent optics with a large variety of atoms and molecules. We use helium buffer gas to cool ^{87}Rb atoms to below 7 K and slow atom diffusion to the walls. Electromagnetically induced transparency in this medium allows for 50% transmission in a medium with initial optical depth D>70 and for slow pulse propagation with large delay-bandwidth products. In the high-D regime, we observe high-contrast spectrum oscillations due to efficient four-wave mixing.

Realization of efficient all-optical switches is a long-standing goal in optical science and engineering. If integrated with modern fiber-optical technologies, such devices may have important applications for optical communication and computation in telecommunication networks. Optical switches operating at a fundamental limit of one photon per switching event would further enable the realization of key protocols from quantum information science. We performed the realization of a fiber-optical switch that is activated at tiny energies corresponding to few optical photons per pulse. This is achieved by integrating fiber-optic and cold-atom technologies with quantum optical techniques for generating slow light propagation and large nonlinear interaction between light beams. Our technique is based on the simultaneous confinement of photons and a small laser-cooled ensemble of atoms inside the microscopic hollow core of a single-mode photonic-crystal fiber. We demonstrated all-optical switching with control pulses containing only a few hundred photons. Potentially, our system may enable control at a fundamental limit of one photon per switching event and creation and probing of strongly interacting many-body photon states.

Mikhail Lukin
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We demonstrated a novel coherent optical medium with high optical depth and low Doppler broadening that offers metastable states with low collisional and motional decoherence. In our approach, helium buffer gas cools 87Rb atoms to below 7 K, while at the same time slowing atom diffusion. We demonstrated that electromagnetically induced transparency (EIT) allows 50% transmission in a medium with initial OD > 70. Slow pulse propagation experiments in this medium yield delays exceeding initial pulse duration by a factor > 25. Efficient four-wave mixing is observed in the high-OD regime, resulting in a pronounced modification of the atomic optical response.

Understanding strongly correlated quantum systems is a central problem in many areas of physics. The collective behavior of interacting particles gives rise to diverse fundamental phenomena such as confinement in quantum chromodynamics, phase transitions, and electron fractionalization in the quantum Hall regime. While such systems typically involve massive particles, optical photons can also interact with each other in a nonlinear medium. In practice, however, such interactions are often very weak. We described a novel technique that allows the creation of a strongly correlated quantum gas of photons using one-dimensional optical systems with tight field confinement and coherent photon trapping techniques. The confinement enabled the generation of large, tunable optical nonlinearities via the interaction of photons with a nearby cold atomic gas. In its extreme, we showed that a quantum light field can undergo fermionization in such one-dimensional media, which can be probed via standard photon correlation measurements.

We demonstrated optical nonlinearities due to the interaction of weak optical fields with the collective motion of a strongly dispersive ultracold gas. The combination of a recoil-induced resonance in the high gain regime and optical waveguiding within the dispersive medium enables us to achieve a collective atomic cooperativity of 275±50 even in the absence of a cavity. As a result, we observed optical bistability at input powers as low as 20 pW. The present scheme allows for dynamic optical control of the dispersive properties of the ultracold gas using very weak pulses of light. The experimental observations are in good agreement with a theoretical mode

Control over the interaction between single photons and individual optical emitter is an outstanding problem in quantum science and engineering. It is of interest for ultimate control over light quanta, as well as for potential applications such as efficient photon collection, single-photon switching and transistors, and long-range optical coupling of quantum bits. Recently, substantial advances have been made towards these goals, based on modified photon fields around an emitter using high-finesse optical cavities. We demonstrated a cavity-free, broadband approach for engineering photon–emitter interactions via subwavelength confinement of optical fields near metallic nanostructures. When a single CdSe quantum dot is optically excited in close proximity to a silver nanowire, emission from the quantum dot couples directly to guided surface plasmons in the nanowire, causing the wire's ends to light up. Non-classical photon correlations between the emission from the quantum dot and the ends of the nanowire demonstrate that the latter stems from the generation of single, quantized plasmons. Results from a large number of devices show that efficient coupling is accompanied by more than 2.5-

fold enhancement of the quantum dot spontaneous emission, in good agreement with theoretical predictions.

Photons rarely interact—which makes it challenging to build all-optical devices in which one light signal controls another. Even in nonlinear optical media, in which two beams can interact because of their influence on the medium's refractive index, this interaction is weak at low light levels. We proposed a novel approach to realizing strong nonlinear interactions at the single-photon level, by exploiting the strong coupling between individual optical emitters and propagating surface plasmons confined to a conducting nanowire. We show that this system can act as a nonlinear two-photon switch for incident photons propagating along the nanowire, which can be controlled coherently using conventional quantum-optical techniques. Furthermore, we discuss how the interaction can be tailored to create a single-photon transistor, where the presence (or absence) of a single incident photon in a 'gate' field is sufficient to allow (or prevent) the propagation of subsequent 'signal' photons along the wire.

Listing of Publications

Acknowledging Slow Light funding

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